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US Army Research Laboratory

Room Temperature Erbium-Doped Yttrium Vanadate ($Er:YVO_4$) Laser and Amplifier

by George A Newburgh

NOTICES

Disclaimers

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Sensors and Electron Devices Directorate, ARL

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14. ABSTRACT

I report on the use of a 976-nm, diode-pumped, erbium-doped, yttrium vanadate (Er:YVO_4), 1603-nm laser and amplifier. In the first of 2 experiments, a 10-mm-long Er^{3+}:YVO_4 slab, cut with its c-axis perpendicular to the laser cavity axis, was pumped in σ-polarization and lased in π-polarization. The laser operated in a quasi-continuous wave regime with nearly 9-W output power and a slope efficiency of about 39% with respect to absorbed power. In a second demonstration, a 25-mm-long Er:YVO_4 slab was pumped in σ-polarization to amplify a π-polarized 1,603-nm fiber-coupled diode source to achieve a small signal gain of 2.1 with a duty cycle of up to 25%. To the best of my knowledge, these have demonstrated the highest efficiency and highest power from an Er^{3+}:YVO_4 laser and the first use of Er:YVO_4 as a nonresonantly pumped amplifier as pumped in the 970- to 980-nm absorption band.

15. SUBJECT TERMS

Er:YVO_4, erbium: yttrium vanadate, laser, amplifier, quasi-continuous wave

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1. Introduction

Lasers in the 1.5- to 1.7-µm wavelength domain have been found to be useful for a range of civilian and military applications, such as measuring carbon dioxide and methane concentrations in the atmosphere using differential absorption LIDAR (DIAL). Laser outputs at 1.5–1.7 µm were obtained by implementing the optical parametric conversion of 1.064-µm, neodymium (Nd)-doped yttrium aluminum garnet (YAG) laser to 1575 nm[1] and 1645 nm,[2] or by the direct generation of 1645-nm Q-switched output using erbium (Er):YAG with resonant in-band diode pumping.[3] For applications requiring remote sensing of aerosols, laser detection and ranging (LADAR), an optical parametric oscillator has been used to convert Nd:YAG laser,[4] or, in another implementation, the Nd:YAG laser has been Raman converted to 1543 nm.[5]

As often is the case, the challenge lies in designing a laser system that is both energy efficient and sufficiently powerful. To date, both the highest continuous wave (CW) laser power (80 W) in the 1.5–1.7 µm wavelength range generated by a bulk solid-state, room temperature (RT) laser gain medium[6] and the greatest pulse energy (120 mJ) in a Q-switched operation[7] have been achieved with the resonant diode pumping ($^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition) of Er^{3+}:YAG. Indeed, in cases where major power scaling is required and thermal loading of the gain medium should be minimized, the use of resonant pumping is a must. However, for applications requiring moderate power, where heat deposition can be tolerated or easily handled, optical pumping by the best developed, most efficient, and the least expensive laser diodes near 980 nm has a practical advantage.

Until now, the most common Er^{3+}-doped laser materials used for pumping at approximately 980 nm involve co-doping by ytterbium (Yb^{3}) ions. The Yb^{3+} ions serve as effective absorbers of the 980-nm pump radiation. Excitation of Er^{3+} ions in this case is achieved through an $Yb^{3+} \rightarrow Er^{3+}$ nonradiative energy transfer to the upper laser level of Er^{3+} – $^4I_{13/2}$. However, while the Yb^{3+} co-doping can simplify laser design, the nonradiative energy transfer presents an additional excitation energy conversion step, thereby increasing heat deposition and reducing overall laser efficiency. The addition of Yb^{3+} ions, usually at a high concentration level (~10%) to the host crystal (e.g., YAG), substantially reduces the thermal conductivity of the host crystal by about a half at concentrations of 10%.[8]

A direct excitation of the Er^{3+} ion via the absorption of 980-nm radiation ($^4I_{15/2} \rightarrow {}^4I_{11/2}$) can be a viable alternative where only moderate power scaling is required. While the quantum defect increases from approximately 5% to approximately 40% in the case of non-resonant versus resonant pumping, the

benefit of using higher brightness and lower cost diode pump sources has motivated recent demonstrations of approximately 980-nm pumped, Yb-free, Er-doped lasers[9,10] emitting at approximately 1.6 µm. So far, the maximum CW laser power from an approximately 980-nm pumped, RT, Er^{3+}-doped eye-safe laser was reported at the 0.4-W level.[11] This motivates further research toward power scaling of approximately 980-nm, diode-pumped, Yb-free, Er-doped crystalline laser materials.

In Section 2, I report on the performance of an eye-safe laser based on an Er^{3+}: yttrium vanadate (YVO_4) single crystal, diode pumped at 976 nm and operating at 1603 nm with near diffraction limited beam quality. The maximum of 9 W of output power in a quasi-CW (Q-CW) regime with the slope efficiency of about 39% with respect to absorbed power has been achieved, which is believed to be the highest efficiency and highest power achieved from an $Er^{3+}:YVO_4$ laser pumped in the 970- to 980-nm absorption band.

LIDAR and LADAR often require amplification of 1.5–1.6-µm semiconductor-generated signals.[16,17] While these powers are adequate in some applications, the ability to increase them past current limits would enable sensing at greater distances. One proven method of increasing the peak powers is the hybrid amplifier: a combination of seed, fiber amplifier, and bulk solid-state gain medium as the final stage. The hybrid amplifier has been shown using the Yb or Nd ion,[18,19] but to date only a few examples of bulk solid-state, Er-doped amplifiers have been demonstrated.[20,21] The near absence of the Er bulk solid-state amplifier is due in no small part to the small stimulated emission cross section ($\sim 5 \cdot 10^{-21}$ cm^2) of Er and the low doping limits imposed by upconversion of the Er ion. These conditions result in long optical pumping path lengths of many centimeters to achieve even modest gains. This can been seen in the few examples of Er-doped amplifiers where a gain of 1.5 requires 60 mm length or Er:YAG.[21]

In Section 3 of this report, we present the result of a non-resonantly pumped $Er:YVO_4$ amplifier with a gain of 2.1 using a high brightness, spectrally combined diode source of M-squared value less than 12 to pump a length of gain medium of only 23.5 mm.

2. Laser Experimental Setup and Results

A simplified optical layout of the laser experiment is shown in Fig. 1. A linearly polarized output of the laser diode module (LDM) emitting at approximately 976 nm with the spectral bandwidth of 4 nm (measured at full width at half maximum intensity level) is used to pump a small slab made of $Er^{3+}(0.5\%):YVO_4$ single crystal with dimensions of $3 \times 5 \times 10$ mm^3. Based on the current availability

of the driver capable of providing the required combination of the drive current and voltage for our LDM, the LDM was operated in a Q-CW regime with the duty cycle not to exceed 10%. We maintained the LDM pump pulse duration at 5 ms, which is much longer than the Er^{3+} upper laser level ($^4I_{13/2}$) lifetime in YVO_4 at RT (3 ms).[12] This signifies that the obtained results are physically the same as in a true CW regime.

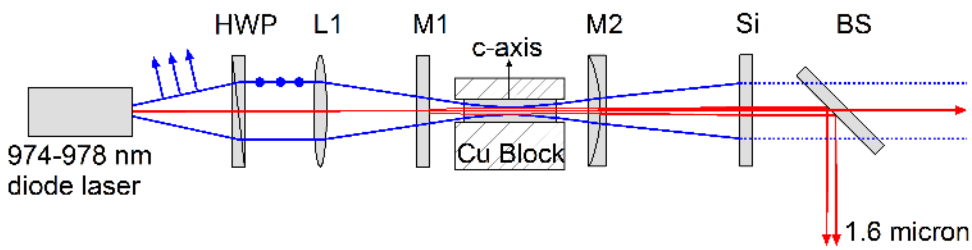


Fig. 1 Experiential setup of the 976-nm, diode-pumped Er(0.5%):YVO_4 laser

The Er^{3+}:YVO_4 slab was cut such that the c-axis was aligned along the thin (3 mm) dimension and was conductively cooled through contact with indium foil by 2 copper blocks. This orientation takes advantage of the high thermal conductivity of Er^{3+}:YVO_4 crystal along the c-axis (~15 W/m*K at RT[13]). The LDM's output was focused by a single, 100-mm focal length lens, L1, and was measured to have a pump diameter of 400 µm in the focal plane (defined at $1/e^2$ intensity level). The measured beam quality of the pump source (M_{pump}^2 ~8) resulted in a Rayleigh range long enough to maintain the pump volume diameter over the entire 10 mm length of the slab. Indeed, the measured Rayleigh range, Z_R= 15 mm in air, implies Z_R = 32 mm in the gain medium as the ordinary refractive index of Er:YVO_4, n_o = 1.96.[14]

In agreement with existing spectroscopic data,[10,11] the 976-nm pump radiation was most effectively absorbed in σ-polarization, and I adjusted the LDM output polarization accordingly by rotation of a half-wave plate (HWP). The 65-mm-long laser cavity was formed by a planar dichroic pump mirror, M1, (high reflectance at 1600 nm, high transmission = 90% at 976 nm) and a plano-concave output coupler, M2. As shown in Fig. 1, in order to properly characterize the laser performance, 2 spectral filters, a polished uncoated silicon (Si) plate and a dichroic beam splitter (DBS), were used to separate the transmitted pump at approximately 976 nm from the approximately 1.6-µm laser output. The uncoated Si filter was found to transmit only 0.25% at 0.976 µm and 53% at 1.6 µm, while the DBS served as an additional spectral filter (R=2% at 0.976 µm, and R= 98% at 1.6 µm).

Based on the limited availability of Er:YVO_4, I used the same Er^{3+}(0.5%):YVO_4 gain element as in previous resonantly pumped lasers experiments.[12] Therefore, the

gain element was not length-optimized for absorption of 976-nm pumping. Indeed, after carefully accounting for the 976-nm reflectivity of the gain element at each of the 2 end faces (R = 9% at 976 nm), it was found that only 12% of the pump power incident on the crystal was absorbed by the gain medium. For that reason, the most meaningful plotting of the laser output power versus the pump power is in terms of absorbed pump power.

A series of laser experiments was performed under Q-CW pumping conditions using an output coupler, M2, with the reflectivity, HR = 97% at 1603 nm with a radius of curvature of 1 m. Figure 2a presents the Q-CW Er^{3+}:YVO_4 laser output at 1603 nm as a function of absorbed Q-CW pump power at 976 nm with a pulse duration of 5 ms and pulse repetition frequency (PRF) of 4 Hz. The laser operation with maximum Q-CW output power of 9 W and optical slope efficiency of 39% with respect to absorbed pump power has been demonstrated.

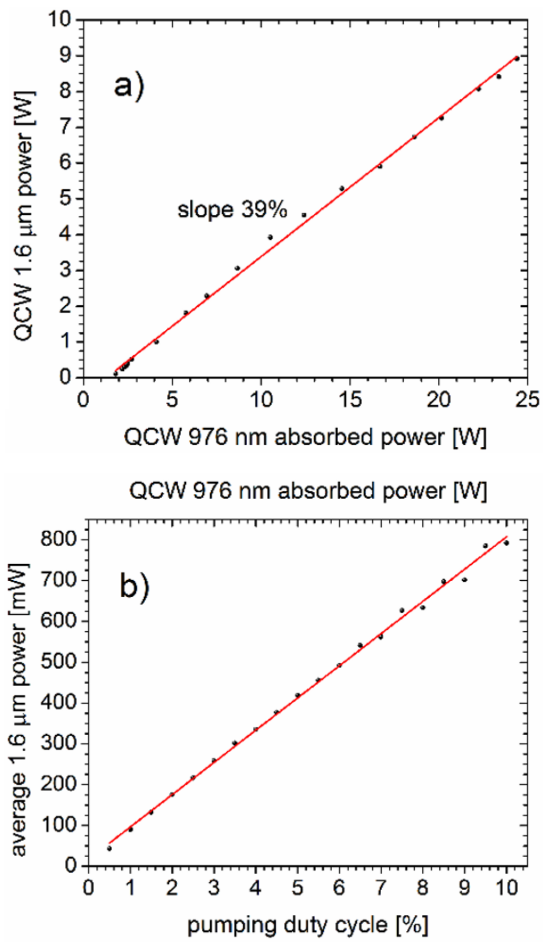


Fig. 2 a) Er^{3+}:YVO_4 Q-CW laser output at 1603 nm as a function of absorbed Q-CW pump power at 976 nm with a pulse duration of 5 ms and PRF of 4 Hz and b) average laser power output vs. duty cycle

To assess laser performance versus laser pump duty cycle, which can be indicative of potential thermal effects in the laser gain medium, I varied the laser PRF within the range of 1 to 20 Hz (duty cycle from ½ to 10%). As can be seen from Fig 2b, there is no evidence of laser performance degradation within the available PRF range—the average laser power scales linearly with the PRF.

As part of this study, I also looked at peculiarities of the laser spectral behavior. What prompted me to do so was the known gain competition of the 2 strongest emission lines of Er^{3+} ion in YVO_4:[12] 1594 nm (σ-polarization) and 1603 nm (π-polarization). In a Q-CW regime, I observed that while the laser emitted most strongly at 1603 nm (π-polarization), the 1594-nm (σ-polarization) output was present to varying degree. Figure 3 indicates the time integrated laser output spectrum at the laser threshold (red) and the maximum power (blue). I found that at the laser threshold, the ratio of integrated 1594-nm power to 1603-nm power was approximately 1:1.4. At pump levels well beyond threshold, the laser output was almosy purely 1603 nm (ratio of 1:43).

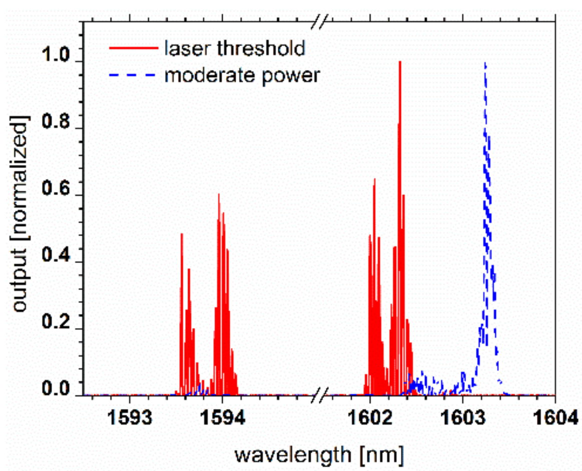


Fig. 3 Spectral output of the Er:YVO_4 laser at laser threshold and maximum power

The observation that the laser output was composed of 2 wavelengths prompted me to carry out a time and spectrally resolved study of the laser emission. Within the 5-ms pump duration, I observed the spectral evolution of the laser output. At the laser threshold, both the 1594- and 1603-nm lines required about 3.9 ms to reach threshold. At the lasing outset, the 1594-nm line dominated, yet as pumping continued, a wavelength switch occurred and the 1603-nm line dominated. The progression from 1594-nm lasing to 1603 nm was found to exist as well under strong pumping conditions, with the 1594-nm lasing going away in less than 1 ms.

Similar behavior was observed in earlier experiments with output wavelength competition in holmium (Ho^{3+}):YVO_4.[15] Detailed spectroscopic analysis versus temperature in that case has shown that local overheating of the gain medium inside the pumped volume sufficiently increases ground state absorption for the shorter wavelength line so that the longer-wavelength one wins the competition. The same appears to be true for the 1603- and 1594-nm lines competition. Clearly, it is fully expected that under RT CW pumping, the Er^{3+}:YVO_4 laser would simply emit at 1603 nm, as was observed previously.[9,11]

Conclusion: The performance of an Er^{3+}:YVO_4 laser diode pumped at 976 nm and operating at 1603 nm produces a maximum of 9 W of output power in a Q-CW regime with the slope efficiency of about 39% with respect to absorbed power has been achieved. This is believed to be the highest efficiency and highest power achieved from an Er^{3+}:YVO_4 laser pumped in the 970- to 980-nm absorption band.

3. Laser Amplifier Setup

The amplifier (Fig. 4) was based on a 3 mm (high) by 5 mm (wide) by 23.5 mm (long) Er(0.5%):YVO_4 rectangular slab cut with its c-axis out of the 5 × 23.5 mm surface. The slab was conductively cooled by a copper block and laser polished on its side surfaces and optically anti-reflective coated in the ranges of 925–1025 nm and 1500–1650 nm. The nominally 0.5%-doped YVO_4 medium was pumped by a spectrally combined 974–978 nm laser diode by a DBS that transmitted 976 nm at 0° and 1600 nm at 45°. A HWP was used to rotate the vertically polarized, 976-nm beam by 90° while the 1000-mm focal length (fl) cylindrical lens (L1) reduced the astigmatism of the pump beam to a few millimeters (Fig. 5). A distributed feedback, 60-mW, 1603-nm laser diode was coupled into a single mode, unpolarized fiber. The 1603-nm wavelength was chosen based on recent experience in a 976-nm, diode-pumped Er:YVO_4 oscillator.[7] The output of the fiber was collimated by a 4.5-mm lens (L5) and redirected by a polarizing beam splitter (PBS) onto the DBS. The colinear propagating 976- and 1603-nm beams were focused by 125-mm fl lens (L2) onto the gain medium in σ and π polarizations, respectively. In a later modification of the first setup (setup #1), a second lens of 250 fl (L3) was added and named setup #2. The lens pair of setup #2 had an effective focal length of about 107 mm.

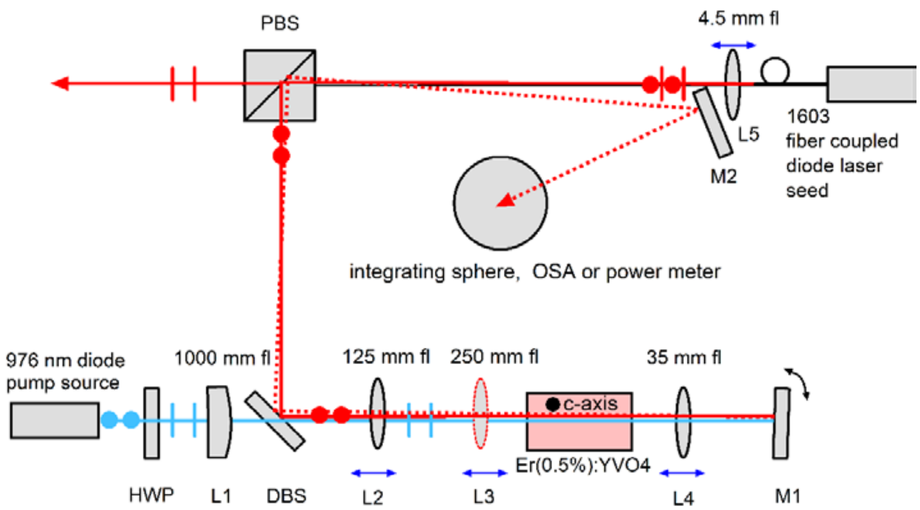
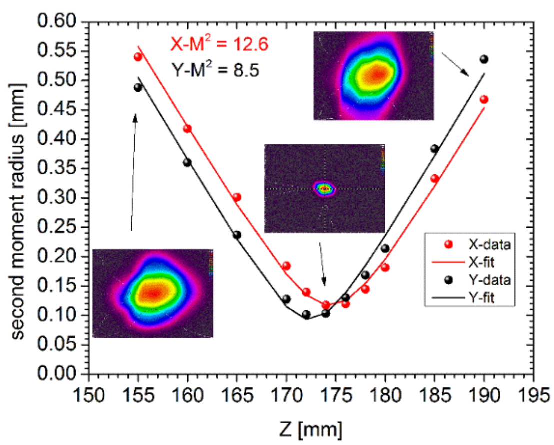


Fig. 4 Top view of the 976-nm diode-pumped Er:YVO_4 amplifier as seeded by a 1603-nm source. The first experiments, setup #1, omitted L3 and setup #2 included L3.



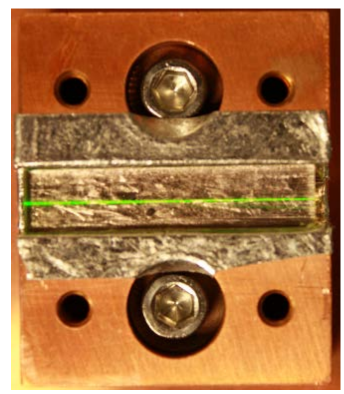


Fig. 5 a) Measurement of the 976-nm pump profile as focused by the 125-mm fl lens (L2). Inserts of the beam intensities are included at and out of focus. b) A trace of the 976-nm pump beam in the Er:YVO_4 slab is shown in green, emission due to upconversion in Er. The copper heat sink measures 25 mm in the long dimension.

The pump and seed beams were re-collimated by a 35-mm fl lens (L4, and returned by a mirror (M1, high-reflective coated for 970 and 1600 nm) at an angle of ~0.01 radian with respect to the initial beam path, resulting in a double-pass pump amplifier. A gold-plated mirror (M2) diverted the amplified beam onto an integrating sphere, optical spectrum analyzer (OSA), or power meter.

A measurement of the pump beam quality was made and is plotted in Fig. 5a. We found that the diode source had an M^2 of 8.5 and 12.6 in horizontal and vertical, respectively, which focused to a diameter of about 250 µm. Based on the refractive index of YVO_4 (~2) and the beam profile of Fig. 5a, the diameter pump beam was

calculated to be less than 500 µm over the entire 23.5 mm length of the Er:YVO_4 slab. A photo of the double-pass, upconverted, 976-nm pump beam (Fig. 5b) showing a width of under 250 µm is in qualitative agreement with this expectation. It was found that in unpumped conditions, that the round trip transmission of the Er:YVO_4 crystal was about 55% and the optical losses about 5%. The 976-nm pump was attenuated to about to about 45% in its initial pass through the slab.

4. Performance Results

Two versions of amplifier were constructed to evaluate the small signal gain of the double-pass Er:YVO_4 amplifier. The first experiment (setup #1) focused pump and seed beam to a diameter of ~250 µm. The 4.5-mm lens (L5) had been chosen so that the single-mode, 1603-nm beam would focus to roughly the same diameter as the 976-nm pump beam. A Q-CW pump pulse duration of 2 ms ranging from 4 to 131 W was used to invert the gain medium. At 1.8 ms into the pump pulse, the 1603-nm seed was turned on for 500 µs. As plotted in Fig. 6a, the seed intensity nearly reached its maximum value using a pump of 2-ms duration at 10 Hz. Given that the unamplified seed suffered a 50% round trip loss, a gain of 1 is reached only with pump powers greater than 40 W. At a pump intensity of 131 W, a net gain of 1.6 is achieved using setup #1, as shown in Fig. 6b. The second amplifier version (setup #2, which included L3) was also tested and yielded a small gain of 2.1, as shown in Fig. 6c and d.

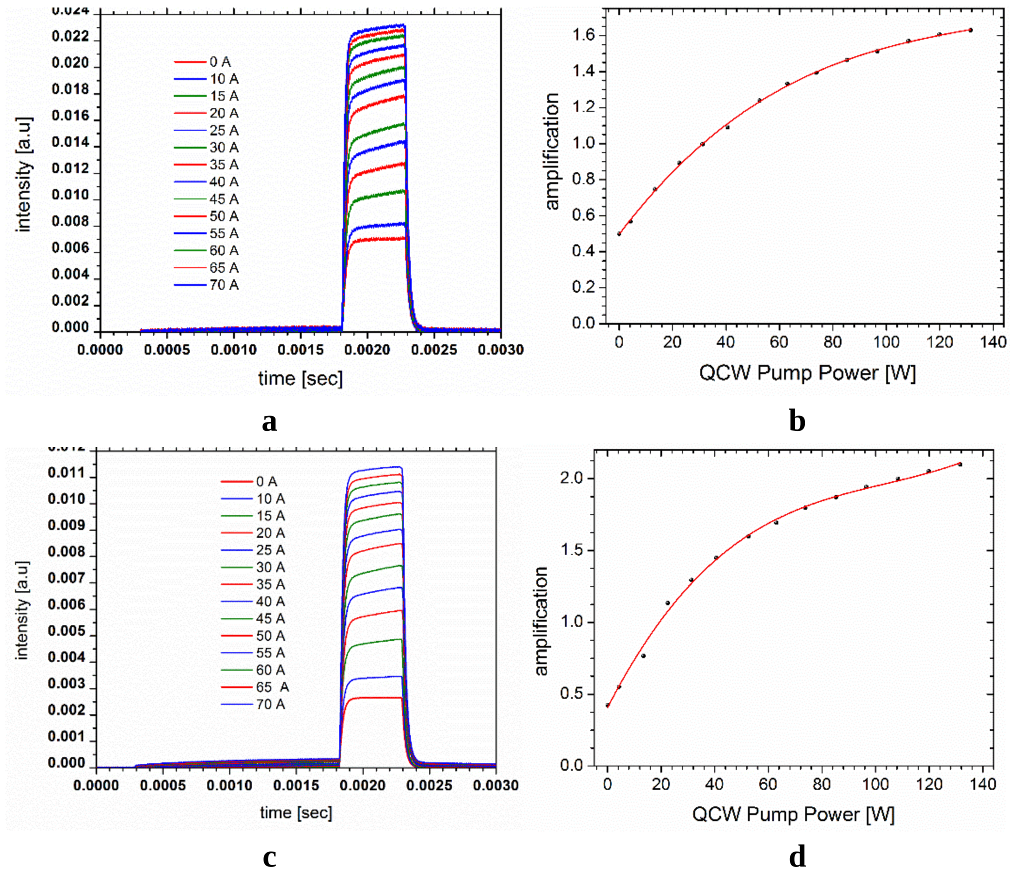


Fig. 6 a) Plot of amplified seed intensity as a function of pump diode current from setup #1. b) Plot of amplifier gain as a function of Q-CW pump power showing maximum gain of 1.6. c) Plot of amplified seed intensity as a function of pump diode current from setup #2. d) Plot of amplifier gain as a function of Q-CW pump power showing maximum gain of 2.1.

The influence of high duty cycle operation on amplifier performance was tested by pumping the amplifier with a diode power of approximately 85-W, 2-ms pump duration from 5 to 125 Hz. As shown in Fig. 7, the amplified seed decreased by only 7% as the PRF increased from 5 to 125 Hz (i.e., 1% to 25% duty cycle). This modest decrease in performance was equivalent to a loss in gain from 2.1 to 1.95. I concluded that heating of the medium was unlikely to be the limiting factor of the amplifier in its current configuration.

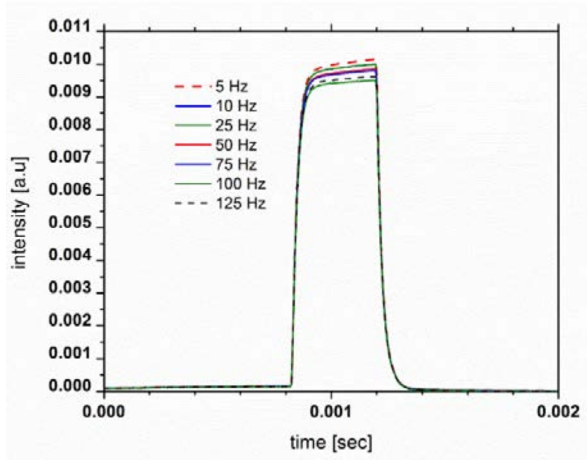


Fig. 7 Intensity of amplified seed for duty cycle ranging from 1%, 2%, 5%, 10%, 15%, 20%, and 25%

5. Conclusions

I have demonstrated a 976-nm, diode-pumped $Er:YVO_4$ laser operating at 10-W Q-CW power at a 39% slope efficiency and a 976-nm, diode-pumped $Er:YVO_4$ amplifier in a double-pass configuration with a net gain of 2.1 with a maximum pump duty cycle of 25%. No appreciable influence to the amplifier gain was found due to high-duty cycle operation.

6. References

1. Shibata Y, Nagasawa C, Abo M. A direct detection 1.6 µm DIAL with three wavelengths for high accuracy measurements of vertical CO_2 concentration and temperature profiles. Proc SPIE. 2013;8894:889406-1–7.

2. Refaat TF, Ismail S, Nehrir AR, Hair JW, Crawford JH, Leifer I, Shuman T. Performance evaluation of a 1.6 µm methane DIAL system from ground, aircraft and UAV platforms. Opt Express,.2013;21(25):30415–30432.

3. Wang X, Fritsche H, Lux O, Eichler HJ, Zhao ZG, Schuett C, Kruschke B. Dual-wavelength Q-switched Er:YAG laser around 1.6 µm for methane differential absorption lidar. Laser Phys Lett. 2013;10:115804.

4. Steinvall O, Persson R, Berglund F, Gustafsson O, Gustafsson F. Using an eyesafe military laser range finder for atmospheric sensing. Proc SPIE. 2014;9080:1690800W1–1690800W16.

5. Mayor SD, Spuler SM. Raman-shifted eye-safe aerosol lidar. Appl Opt. 2004:43 (19):3915–3924.

6. Kudryashov I, Katsnelson A, Ter-Gabrielyan N, Dubinskii M. Room temperature power scalability of the diode-pumped Er:YAG eye safe laser. Las. and Electro-Opt./Quant. Electron. and Laser Sci. Conf., 2009 Jun, Baltimore, MD, paper CWA2.

7. Larat C, Schwarz M, Lallier E, Durand E. 120mJ Q-switched Er:YAG laser at 1645 nm. Opt Express. 2014;22(5):4861–4866.

8. Aggarwal RL, Ripin DJ, Ochoa JR, Fan TY. Measurement of thermo-optic properties of $Y_3Al_5O_{12}$, $Lu_3Al_5O_{12}$, $YAIO_3$, $LiYF_4$, $LiLuF_4$, BaY_2F_8, $KGd(WO_4)_2$, and $KY(WO_4)_2$ laser crystals in the 80–300 K temperature range. J Appl Phys. 2005;98:103514-1–103514-14.

9. Sulc J, Jelinkova H, Ryba-Romanowski W, Lukasiewicz T. 1.6 µm microchip laser. Laser Phys Lett. 2009;6(3):207–211.

10. Sokolska I, Heumann E, Kück S, Łukasiewicz T. Laser oscillation of Er^{3+}:YVO_4 and Er^{3+},Yb^{3+}:YVO_4 crystals in the spectral range around 1.6 µm. Appl Phys B. 2000;71:893–896.

11. Sulc J, Jelinkova H, Nemec M. Room temperature operation of CW diode pumped Er:YVO_4 laser at 1.6 micron. Optical Society of America ASSP LACSEA LS C 2010, 2010, paper ATuA27.

12. Ter-Gabrielyan N, Fromzel V, Ryba-Romanowski W, Lukasiewicz T, Dubinskii M. Spectroscopic and laser properties of resonantly (in-band) pumped Er:YVO_4 and Er:$GdVO_4$ crystals: a comparative study. Opt Mater Express. 2012;2(8):1040–1049.

13. Zagumenny AI, Popov PA, Zerouk F, Zavartsev YuD, Kutovoi SA, Shcherbakov IA. Heat conduction of laser vanadate crystals. Quantum Electron. 2008;38(3):227–232.

14. Zelmon DE, Lee JJ, Currin KM, Northridge JM, Perlov D. Revisiting the optical properties of Nd doped yttrium orthovanadate. App Opt. 2010;49(4):644–647.

15. Newburgh A, Fleischman Z, Dubinskii M. Highly efficient dual-wavelength laser operation of cryo-cooled resonantly (in-band) pumped Ho^{3+}:YVO_4 laser. OptLett. 2012;37(18):3888–389.

16. Henrie J, Bowers MS, Afzal R, Jenson B, Grobmyer JE. Compact, high-power, eye safe fiber laser for LADAR. Proc SPIE. 2008:6952 695204-1.

17. Bowers MS, Savage-Leuchs M, Liu A, Eisenberg E, Henrie J, Jenson B, Borschowa L, Miller C. High peak power, short-pulse, eyesafe fiber laser for radar applications. Proc SPIE. 2005:5792.

18. Pouysegur J, Guichard F, Zaouter Y, Hanna M, Druon F, Hönninger C, Mottay E, Georges P. Hybrid high-energy high-power pulsewidth-tunable picosecond source. Optics Lett. 2015;40(22):5184.

19. Wei D, Ma X, Zhu R, Zhou C, Liu J, Zhu X, Chen W. High energy single-frequency double-pulse hybrid MOPA system. Laser Phys Lett. 2015;12:095004.

20. Tan Y, Ma L, Akhmadaliev S, Zhou S, Chen F. Ion irradiated Er:YAG ceramic cladding waveguide amplifier in C and L bands. Optical Mat Express. 2016;6(3):711.

21. Larat C, Schwarz M, Lallier E, Durand E. 120mJ Q-switched Er:YAG laser at 1645 nm. Optics Express. 2014;22(5):4861.

List of Symbols, Abbreviations, and Acronyms

CW	continuous wave
DBS	dichroic beam splitter
DIAL	differential absorption LIDAR
Er	erbium
fl	focal length
Ho	holmium
HWP	half-wave plate
LADAR	laser detection and ranging
LDM	laser diode module
Nd	neodymium
OSA	optical spectrum analyzer
PRF	pulse repetition frequency
Q-CW	quasi-CW
RT	room temperature
Si	silicon
YAG	yttrium aluminum garnet
Yb	ytterbium
YVO_4	yttrium vanadate

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